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SIMPLE CONSTRUCTION AND PERFORMANCE OF A CONICAL PLASTIC CRYOCOOLER

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Low power cryocoolers with conical displacers offer several advantages over stepped displacers. The described fabrication process allows quick and reproducible manufacturing of plastic conical displacer units. This could be of commercial interest, but it also makes systematic optimization feasible by constructing a number of different models. The process allows for a wide range of displacer profiles. Low temperature performance as dominated by regenerator losses, as well as several related effects are discussed. In addition a simple device is described which controls gas flow during expansion.

Key words: Composites; conical displacer; cryocooler; flow controller; low power refrigeration; low temperature; plastic; refrigeration; regenerative cooler; Stirling cycle.

1. Introduction

The widespread use of low temperature devices by non-specialists depends heavily on the availability of suitable coolers. Practical solutions to this problem will stimulate research along lines that are presently unattractive. Zimmerman [1] pioneered the development of plastic Stirling coolers with gap regeneration to cool a SQUID device directly. The emphasis is on very low magnetic interference levels (dictating the use of plastics) and very low cooling power. A cooler's performance, as can be shown from elementary principles, improves significantly at low temperatures if multiple stages are used. If one ignores the increase in void volume, adding additional stages is always advantageous. However, all individual stages need separate machining and careful assembly. An attractive alternative is a tapered displacer, which can be considered as consisting of an infinite number of stages. Du Pré and Daniels [2] experimented with such a conical displacer in 1971 and Myrtle et al. [3] successfully built a plastic version suitable for SQUID applications. These units still require a lot of careful machining. In addition, constructing a viable machine from a bare unit is time consuming. We felt the need for a different manufacturing scheme that

- is simple,
- has inherently better reproducibility,
- allowes more design flexibility, and
- reduces the time spent in completing the unit.

2. Conical displacer

In Stirling coolers all losses are distributed along the length of the displacer-regenerator, except for the discrete radiation shields. From the thermodynamic point of view therefore, distributed cooling represents the main advantage of Stirling coolers with a conical displacer compared to their stepped counterparts. The shape of the cone determines the distribution of the cooling power.

There are several more subtle effects however. Cool-down is slightly faster because of the lower mass of the displacer. The gas is expanded within an annular gap, whereby thermal contact during expansion is improved and (the more favourable) isothermal expansion can be achieved even at low temperatures. Several effects depend on the width of the annular gap. At low temperatures the regenerative losses are dominant. Although this loss is mainly due to the plastic, it is still important to keep the thermal resistance of the gas gap low by means of a narrow gap. At higher temperatures shuttle heat transfer losses are more important and a wider gap with corresponding higher thermal resistance becomes attractive. The annular gap of a conical displacer depends on the angle of the taper and varies during a stroke.

A more important issue is the void volume. Zimmerman [1] found that his nylon displacers contracted 1% more than the glass fibre reinforced epoxy cylinder during cool-down. In cylindrical stages it is easy to compensate for axial contraction. However the radial contraction causes an appreciable void volume. At a typical stage length of 150 mm, the annular void volume associated with this 1% differential contraction corresponds to about 3 mm dead stroke - compared to a typical 6 mm active stroke. Since regenerator losses are proportional to the total mass flow squared [4], this effect roughly doubles regenerator losses. Conical displacers have different properties: The gas gap widens during the upgoing stroke and no additional static gap is needed for the gas flow. Axial correction can compensate for radial contraction of a linear cone. However, when either the taper is nonlinear or the contraction is inhomogeneous (temperature gradient) this is impossible and may result in significant void volumes. Therefore in a conical design the sleeve should contract slightly more than the displacer. In that case the void volumes are in the gaps at higher temperatures, where they are less important or even favourable (higher thermal resistance). The only void volume at low temperature is located at the narrow tip, which can be easily filled.

Probably the most important advantage of conical displacers is in construction. When difficult machining can be avoided, this shape clearly favours simple, single step manufacturing processes.

3. Manufacturing

It is not feasible to machine both tapered displacer and sleeve from plastic rods with sufficient accuracy to get a reasonable fit. The obvious solution is to use one of these as a mould for the other; a perfect fit is guaranteed. Myrtle et al. [3] machined the displacer from rods and wrapped glass fabric with epoxy resin around it to obtain the sleeve. However, machining a long narrow displacer from glass fibre epoxy is tedious to say the least. It has to be done by sections, which adds critical aligning steps to the process. We wrapped the sleeve around a brass cone, and tried to cast the displacer in this sleeve afterwards. Uneven distribution of the glass fibres within the epoxy resin made the displacer warp seriously at cryogenic temperatures. This suggested the use of glass powder instead of fibres, but small irregularities in the inner surface of the sleeve prevented a reliable release. Therefore we prepared a special mould from the brass cone. A professional casting rubber contracted about 0.5% (elastically), rendering the mould useless. We obtained good results with unfilled casting wax saturated with fine sand to eliminate contraction (causing cracks) during congealing.

The entire manufacturing scheme is illustrated in figure 1. The critical properties of the cone are sufficient roundness and a straight axis, rather than the precise diameters. The brass cone was machined in about one day on an ordinary lathe, and can be used many times. This garantuees reproducibility.

After coating the brass cone with a parting agent, a layer of glass fibre ribbon is wrapped around it using Stycast 1266 epoxy resin (Emerson & Cuming). Next, a helium diffusion barrier of 5 μm manganin foil and the aluminum tip are secured with a second wrapping. Electrical leads and thermocouples are thermally anchored and protected by the third and final layer. Supports for radiation shields can be built up from glass fibre ribbon or aluminum. Black Stycast 2850 FT (with catalyst 24LV, Emerson & Cuming) is cast in the flange mould attached to the brass cone (fig. 1a). Threaded holes are formed in the plastic by embedding nuts. The entire sleeve is cured at room temperature. Then the brass is released by force, and the supports for radiation shields are machined to the right size.

Figure 1b shows the manufacturing of the displacer mould. The melted wax/sand mixture is cast around the preheated brass cone. After insulating with glass wool, water cooling causes congealing to start from below. An anchor at the bottom prevents an upward shift of the wax during contraction. In this way the contraction can actually be used to force a perfect fit. The brass cone is pulled free at room temperature.

Figure 1c shows casting of the displacer in the wax mould. We use a mixture of fused silica (-200 mesh) and Stycast 1266 epoxy. The ratio of the powder and resin components is 180 powder: 100 component A : 28 component B in parts by weight. Immediately after preparation, the mixture is vacuum treated to remove air bubbles and then injected into the mould. After cure at room temperature the wax is melted. Small surface irregularities are corrected with sandpaper and the displacer is machined to the right length. The glass powder/epoxy mixture is very homogeneous and we found no warp at cryogenic temperatures. However, should the need arise, the displacer can be made flexible by segmenting it and interconnecting the pieces with wire (a single nylon fibre in the casting can be pulled out easily after cure, leaving a convenient channel). With another trivial extension of the moulding process the displacer could be made hollow to decrease thermal conductivity and thermal mass.

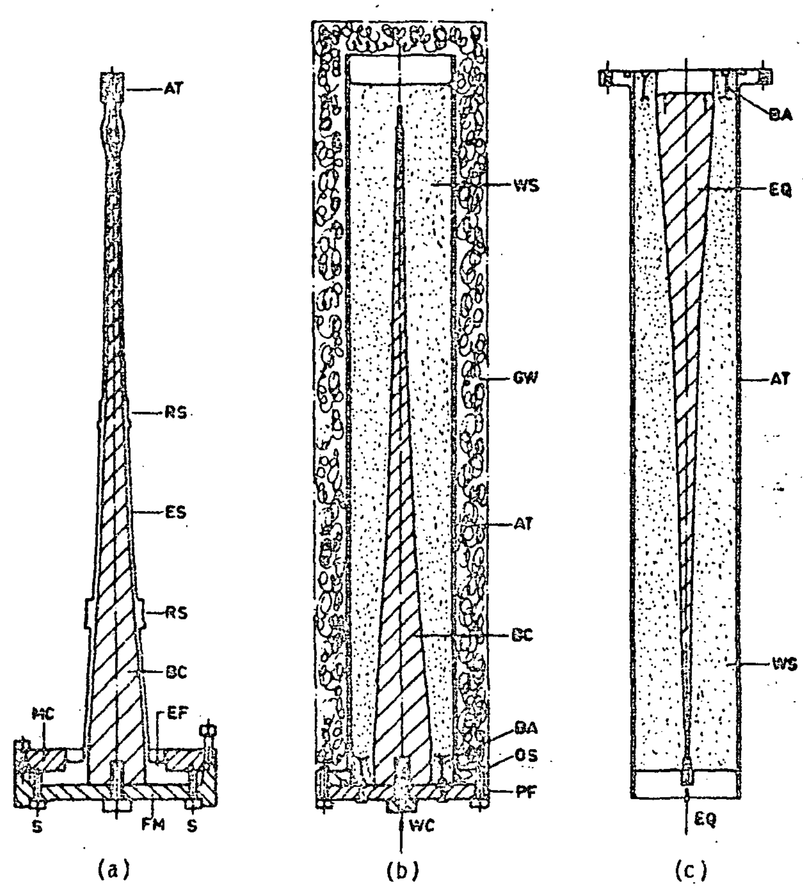

Fig. 1. Manufacturing: (a) The glass fibre epoxy sleeve (ES) is wrapped around the brass cone (BC), with an aluminum tip (AT). An epoxy flange (EF) is cast in a covered (MC) flange mould (FM). Screws (S) may be used to form threaded holes. Supports for radiation shields (RS) are built up and machined after cure. (b) A wax/sand mixture (WS) is cast around the brass cone (BC) within an aluminum tube (AT), and insulated with glass wool (GW). Water cooling (WC) through an insulating flange (PF) determines the direction of congealing. Brass anchors (BA) hold the wax down. (c) Glass powder/epoxy mixture (EQ) is injected into the wax mould.

The photograph (fig. 8) shows the different components. Except for a lathe, no special tools are needed. At the moment the entire process takes about 40 man hours in the laboratory. The main part is consumed by preparation. For a small series a significant gain is possible. A more detailed description of the process can be obtained from the author on request.

4. Results

We compared the dimensions of the plastic displacer and brass cone at room temperature and found the displacer to be about 0.05 mm smaller in diameter along the entire length. The tip of the displacer was shortened until it fitted the sleeve exactly, and this length corresponded to the length of the brass cone within 0.1 mm. Then the tip was lengthened by a 1 mm piece of aluminum. The displacer was now completely free to move in the sleeve. The top of the fully inserted displacer shifted less than 0.1 mm after warming up to room temperature, indicating negligible difference between contraction of sleeve and displacer. At cryogenic temperatures the displacer was still free to move and rotate in the sleeve, indicating negligible warp.

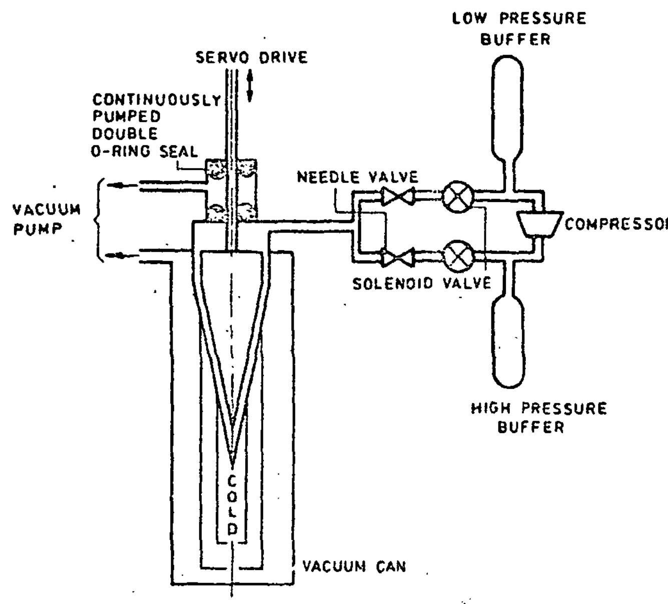

Fig. 2. Experimental setup. The cold space inside the vacuum can is surrounded by radiation shields and superinsulation.

Figure 2 shows a diagram of the experimental setup. The displacer unit with radiation shields and superinsulation is mounted in a continuously pumped vacuum can. For experimental purposes the displacer is driven by a servo motor (electronically controlled) through a vacuum pumped double O-ring seal to avoid contamination of the helium. A small, standard, rubber membrane air compressor is used to compress the helium in a closed circuit. Solenoid valves control compression and expansion in the displacer unit.

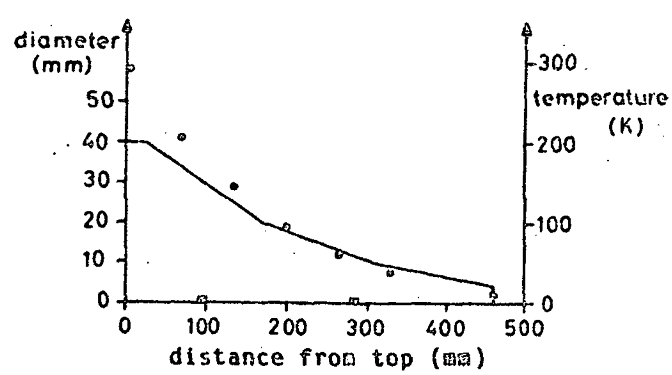

Fig. 3. Diameter (solid line) and temperature (dots) along the length of the cone. Tip temperature measured with germanium resistor, others with thermocouples. Positions of the two radiation shield supports are indicated at horizontal axis.

The first experimental results are promising: At a 1 second period, a 6 mm stroke and a 0.42 to 0.10 MPa (absolute) pressure cycle it cooled down to 10.1 K in 18 hours. Temperature distribution and dimensions of the cone are indicated in figure 3. The temperature at the tip rises 0.4 K with a 1 mW heat load. At present the lowest temperature is limited by the performance of the compressor, and we intend to improve the system in the near future. Although the manganin shield inside the plastic sleeve wall of this unit was damaged during manufacturing, it took about 5 hours before the tip temperature started to rise noticeably due to helium diffusion if pumping was discontinued.

5. Gas pressure and displacement

Several parameters are important in optimizing the operation of a cooler. The gas pressure and displacement waves are of general importance for any regenerative system. At temperatures below about 20 K the regenerator losses are dominant. The gas flows in an axial temperature gradient dT/dz and the heat load on the regenerator is proportional to the thermal capacity of the gas flow $\dot{m}C$ and the thermal gradient. Heat exchange with the plastic is not perfect. This can be expressed as a thermal impedance Z_T. The temperature difference δT between gas and plastic (reference) is given by

$$\delta T = Z_T \dot{m} C \frac{dT}{dz}$$

The net regenerator loss $\dot{Q}_{reg}$ is a time averaged product

$$\dot{Q}_{reg} = \langle \dot{m} C \delta T \rangle_t = \langle (\dot{m}C)^2 Z_T \rangle_t \frac{dT}{dz}$$

In many textbooks a basic distinction is made between Stirling (piston), Gifford-McMahon (continuous compressor with valves) and Vuilleumier (regenerative thermal compressor) cycle. Indeed the room temperature arrangements and their inherent limitations (high drive forces and sealing, lower efficiency, high temperature construction and low compression ratio, respectively) are quite different, but at the low temperature end the cycles are very similar. The lower regenerator heat load of a constant density cycle (the theoretical Stirling cycle) can in fact be achieved by moving stacked displacer segments down (or up) one by one (analogous to the ripple that passes through a queue of cars waiting at the fast food drive-in). The conventional single displacer system, however, leads to the 5/3 times higher heat load of a pressure controlled system.

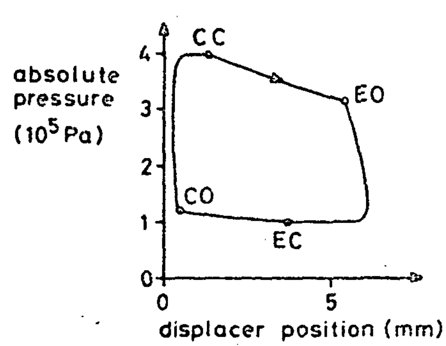

Fig. 4. Pressure - displacement oscilloscope trace. Compression valve opens at CO and closes at CC. Expansion valve opens at EO and closes at EC.

There are still some possibilities left to reduce the regenerator heat loss significantly by manipulating the pressure and displacement cycle. As was pointed out above, it is very important to keep the low temperature void volume low compared to the swept volume. This reduces the unnecessary part of the mass flow. Figure 4 shows the pressure - displacement oscilloscope trace of the actual cycle employed in our machine. The refrigeration power is directly proportional to the area enclosed in the pressure - displacement diagram. The total mass flow corresponds to the difference between maximum and minimum of the product of pressure and displacement (at EO and CO). In a regenerator loss dominated machine like ours, it is important to truncate the rectangular cycle of a typical Gifford-McMahon machine as shown (CC to EO and EC to CO) by timing the valves properly. In this way a small amount of the available refrigeration power is sacrificed, but the regenerator losses are reduced significantly by the decrease in mass flow. Typical numbers are 10% reduction of refrigeration and an improvement of about a factor two in regenerator loss. The ideal case would be truncation along a line of constant amount of gas (hyperbole), i.e. zero mass flow. Unfortunately the unavoidable room temperature volume at the top of the displacer limits the pressure drop between CC and EO.

Another possible improvement involves the time dependence of the mass flow. In the case of a purely resistive thermal impedance (e.g. a narrow gas gap) a square wave is optimal. A sine wave is only a factor $\pi^2/8$ worse, but peaked functions are clearly less desirable. As indicated by Radebaugh [4] the thermal penetration depth in the plastic will usually dominate at low temperatures. In that case the thermal impedance has an imaginary part. This introduces a 45 degree phase shift and corresponding $1/\sqrt{(\text{frequency})}$ dependence in all Fourier components [5]. The phase shift introduces a extra factor of $1/\sqrt{2}$ for a sine wave. In this case, determining the optimum wave form involves some mathematics. The optimal solution results in an improvement of only about 20% compared to the sine wave.

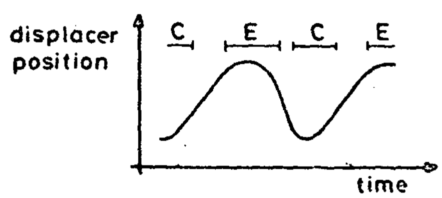

Fig. 5. Displacer movement. C: Compression valve open. E: Expansion valve open.

However, in practical valve operated coolers the mass flow cycle is highly asymmetric and peaked. The performance can be improved significantly by smoothing the gas flow. Our experimental setup allows full electronic control of the displacer movement. Figure 5 shows a typical oscilloscope trace of the non-sinusoidal movement employed in our machine. Most of downward gas transport occurs during the upward displacer movement at high pressure. Most of the upward gas transport occurs during expansion when the displacer is at top position. Therefore more time is spent in raising the displacer and near the top position.

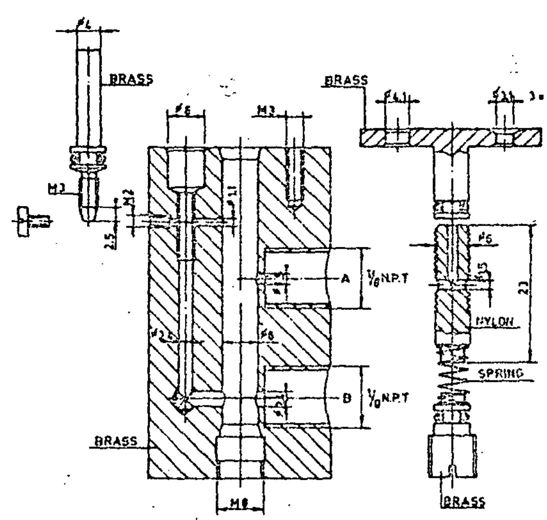

Fig. 6. Gas flow controlling device. Gas flows through needle valve at the left to the outlet port B. The nylon piston at the right stabilizes the pressure difference over the needle valve by closing the inlet port A.

Smoothing of the pressure cycle during expansion and compression is usually achieved by means of a needle valve. The mass flow through such a constriction generally depends on both the pressure difference and the average pressure at inlet and outlet port. This gives rise to a long tail in the pressure decrease as a function of time (a hyperbolic cotangent for laminar flow). The time derivative of the pressure, which represents the mass flow when the displacer is stationary, is highly peaked. A simple solution would be to use a spring-loaded needle valve which opens when the pressure difference over the constriction drops. It is difficult, however, to adjust the flow characteristics of such a device while in operation. Figure 6 shows a more sophisticated device, which essentially consists of a pressure regulator and needle valve in series. Expansion to the low pressure outlet is controlled by the needle valve. The pressure difference over the needle valve is stabilized by a spring-loaded nylon piston which closes the high pressure inlet when necessary. The flow through the device now depends on pressure at the outlet only. In figure 7 the oscilloscope traces of expansion through this device and through an ordinary needle valve can be compared. The lowest temperature in our cooler improved about 0.8 K with this modification, and the effect should be even more important at lower temperatures. Several versions are possible, e.g. a membrane instead of a piston, a stem or needle instead of a poppet valve, an adjustable spring, etc. We suppose that this device can be used in other fields as well. A similar device could be designed for compression, but this is a less critical part of the cycle. Regenerator heat load during compression is low because the displacer is near the bottom position, and compression is inherently more linear than expansion.

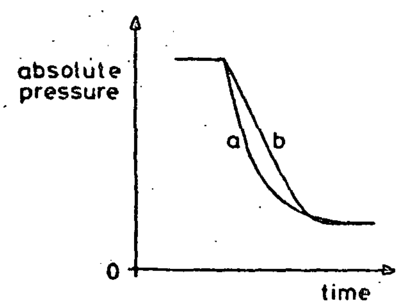

Fig. 7. Expansion through ordinary needle valve (a) and through flow controlling device (b). Note that the time derivative, representing the mass flow, is highly peaked in (a) but almost perfectly constant in (b).

6. Future work

Besides improving the current performance by operating at somewhat higher pressures, we intend to build several different units in the near future. An obvious improvement would be a hollow displacer. This is only relevant at the high temperature section. A significant improvement is expected in low temperature performance by incorporating a higher heat capacitance, e.g. lead particles or He on charcoal, in the plastic. Because the loss from static conduction is negligible at low temperature, regenerator losses can also be reduced by using materials with a higher thermal conductivity. We hope to perform a rather detailed computer analysis including all relevant details, in order to optimize low temperature performance. Another simple extension would be a small, low pressure Joule-Thomson stage using the gas from the regenerative cycle to prevent impurity build up. The gas lines can be embedded in the plastic sleeve. A similar experiment on a stepped cooler [6] indicated that this approach is feasible.

7. Summary

Multiple stage plastic cryocoolers require accurate machining of all separate stages and careful assembly to achieve a close fit of the displacer within the cylinder. Conical displacers are thermodynamically attractive, but were thus far more difficult to make than multiple staged designs. This paper describes a simple process to make both the cold finger and the displacer from a single conical mould. Vacuum flange, cold tip and supports for radiation shields are included. Thermocouples and electric wiring are embedded in the plastic. The first experimental results in low temperature performance are promising. In a laboratory the entire process takes about 40 man-hours, which seems a reasonable starting point for small scale production. The reproducibility of the product allows for systematic performance optimization by constructing a number of different models. The flow controlling device for expansion, and several other improvements concerning regenerator loss may be useful for other projects as well.

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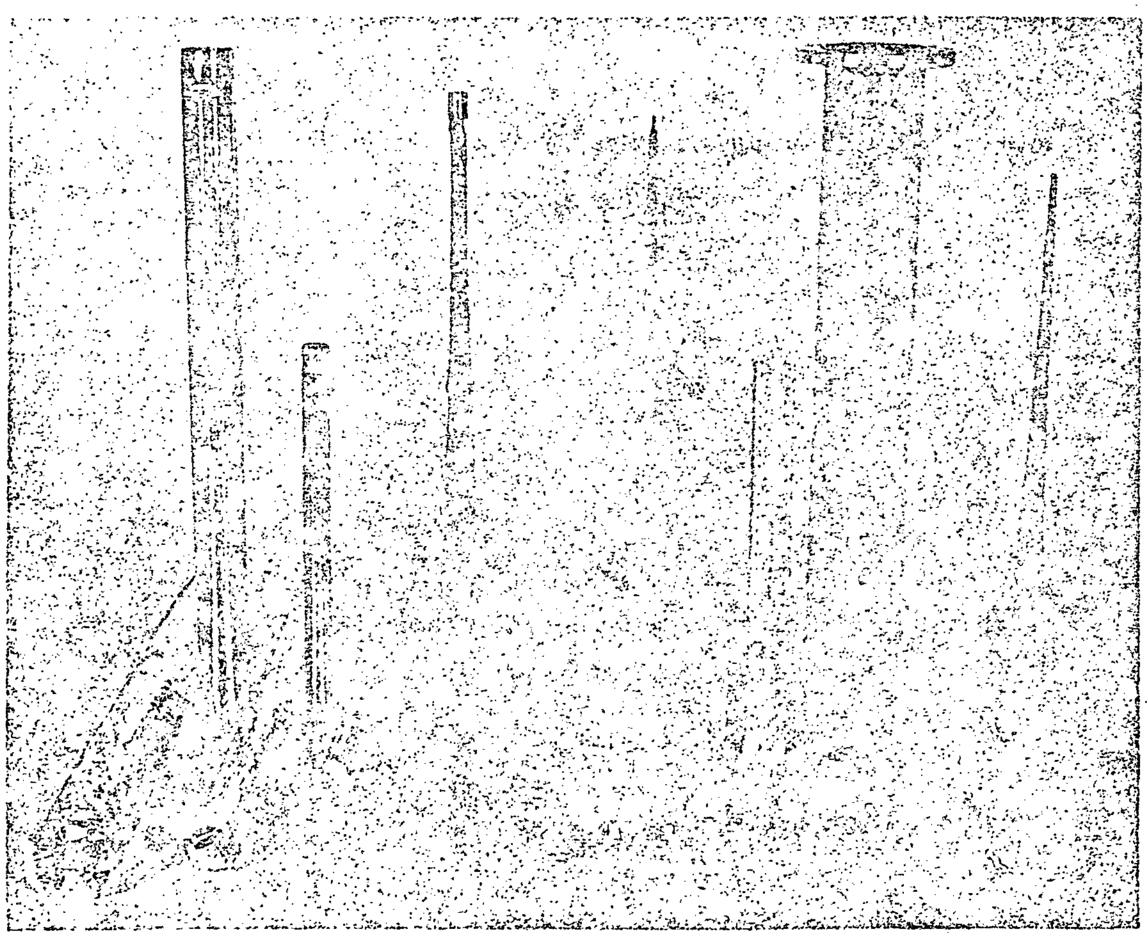

Fig. 8. From left to right: Superinsulation packs and radiation shields, glass fibre epoxy sleeve, brass cone with flange mould and cover, 30 cm scale, wax/sand mould with flange, glass powder/epoxy displacer.